Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

MAY 1978 No 1270 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1270, May 1978, Vol. 107

551.5:06(b)

THE FUTURE DEVELOPMENT OF THE METEOROLOGICAL OFFICE

By the Director-General, B. J. MASON, C.B., D.Sc., F.R.S.

SUMMARY OF DEVELOPMENTS OVER THE LAST TEN YEARS

A great many changes have taken place in the Meteorological Office during the last decade. The Weather Service has been extensively modernized and reorganized around the very powerful IBM 195/158 computer system and the automated telecommunication complex, the forecasting now being firmly based on the most advanced numerical models in operational use. Supporting services, for example observational practices and instrument research and development, have also been reorganized and strengthened. New branches have been established for hydrometeorology and for systems development. There has been a major expansion in research, with new and powerful groups established in cloud physics, geophysical fluid dynamics, satellite meteorology, stratospheric dynamics and chemistry and radar meteorology. The Meteorological Research Flight has been greatly strengthened by the acquisition of the superbly equipped Hercules flying laboratory. Our effort in the numerical modelling of weather and climate stands comparison with that of any other single institution in the world. Recruitment, especially of young scientists, has improved dramatically and much of our scientific progress is being made by scientists still in their twenties or early thirties. Our accommodation has greatly improved with the building of the Richardson Wing and the laboratory at Beaufort Park. On the international scene we have been major participants in World Weather Watch (WWW) and the GARP Atlantic Tropical Experiment (GATE) and will be making a substantial contribution to the forthcoming First GARP Global Experiment (FGGE) in 1978–79. Most important of all, we have expanded and improved our services to aviation, industry and the general public and have achieved much greater efficiency and productivity as is illustrated by the following statistics:

	1965/66	*(1977/78 estimated)*
Gross budget	£7·2 million	£28·2 million
Revenue	£1·7 million	£8·7 million
	1965	*1977*
Non-industrial staff	3159	2970
Aviation forecasts	1·24 million	2·18 million
Non-aviation enquiries	1·16 million	1·97 million

Climatological enquiries	9819	28 986
Calls on ATWS	7·75 million	19·04 million
Telecommunication traffic at Bracknell (groups/day)	1·06 million	3·32 million
FAX charts/day	274	1303

We may now fairly claim to be, in many ways, one of the most advanced and efficient meteorological services in the world, while our scientific contribution is surpassed only by the United States. All this has been achieved on a budget which has grown very little in real terms over the period and by a staff which is rather smaller now than ten years ago. But this is no reason to rest on our laurels; there is still much to be done; the major problems of meteorology are still unsolved. In the harsh economic climate that now prevails we must do even better by sharpening our objectives and making sounder and harsher judgements of priorities. In a rapidly developing science we must have some growth points even if this means hard pruning of less important projects.

Major projects in course of completion

Of the major projects in the first 10-year plan only the following are outstanding:

(a) *The Mark 3 radiosonde*

The lengthy delays in this project have been somewhat disappointing but most of the problems have now been overcome and the first station, Aughton, was commissioned in November 1977 and Crawley in February 1978. Thereafter the remaining UK stations will be installed at monthly intervals. The whole program should be completed by mid-1979.

(b) *Phase III of the automated telecommunication system*

Phase III of the automated telecommunication system, designed around a pair of Ferranti Argos 700S computers that will supplement the present Marconi Myriads, will provide a much more powerful and flexible facility capable of handling transmission speeds of 4800 bits/s on the Main Trunk and other major circuits. Facilities for the transmission of grid-point data, digital facsimile, bulletin compilation and editing and message routeing will be greatly increased. There has been some delay because of the difficulties experienced by Ferranti in the software development but the complete system should be delivered in the summer of 1978 and be fully operational by early 1979.

(c) *METEOSAT and TIROS N satellite programs*

The first flight model of the European geostationary satellite (METEOSAT) built and operated by the European Space Agency was launched in November 1977. The only serious worry concerned the Darmstadt ground station for controlling the satellite and processing the meteorological data, where the ICL 2980 twin computer system was seriously delayed because of incomplete and unsatisfactory software. However, the worst problems have been overcome and pictures from METEOSAT were received within a few days of launch. The pictures are of high quality and should provide valuable data for research and forecasting.

Funds for the operation of the first satellite throughout its useful life now seem assured but there is no provision (and little immediate prospect) for the prompt launching of the second flight model, if the first should fail. This is a

very serious situation because if the first satellite does fail, and urgent steps are not taken to ensure an early second launch, METEOSAT will not be able to contribute to the First GARP Global Experiment (FGGE).

It seems only logical and sensible that, if METEOSAT proves cost-effective, it should be followed by further similar operational satellites forming part of WWW well into the 1980s. But again, political and financial difficulties, centred on the fact that national meteorological services rather than the space agencies will probably have to foot the bill at this stage, have prevented any agreement or decision from being reached.

As far as UK participation is concerned, we have assumed that the costs of a long-term operational METEOSAT program would have to fall on the Meteorological Office budget and suitable sums have been inserted in estimates for the years 1980 and beyond.

Our program to provide stratospheric sounding units (SSUs) to obtain stratospheric temperature profiles from the next series of US operational polar-orbiting satellites (TIROS N) is proceeding satisfactorily. Orders have been placed for eight such units; the first has been delivered to the USA for engineering tests and the remainder should be available at six-monthly intervals. There should therefore be no difficulty in meeting the TIROS N schedule which, in any case, has been delayed and may be delayed further by the failure of the US manufacturer to produce a satisfactory tropospheric sounding unit (TSU) with which our SSU will be integrated. Strong efforts are being made to launch the first TIROS N by mid-1979 during the operational phase of FGGE.

Our new satellite receiving station at Lasham will enable us to receive all the required satellite pictures and some of the sounding data from both METEOSAT and TIROS N but we shall need to mount a substantial data-processing effort in order to evaluate the quality of the products and use them in day-to-day operations. This is well in hand.

New objectives and programs

The scope for overall expansion of our activities will be severely limited by the current economic situation, at least for the next few years, so that new projects will require strong justification and will, in general, be possible only if some existing and less promising projects are curtailed. The review, assessment and monitoring of all our major activities and projects will be the responsibility of the new Program Review Committee. Its task will be to decide scientific priorities, achieve a proper balance between services and research, assess the benefit of projects in relation to their cost, and ensure the most efficient utilization of available resources. It will also provide the main guide-lines for the preparation of detailed estimates for ten years ahead. A comprehensive Operational Plan for the next decade is now being prepared and will set out all our major activities, programs and projects in both functional and organizational patterns.

Our main objectives must continue to be the improvement of weather forecasts in accuracy and in range, to improve their presentation and dissemination both to specialized users and to the general public, and to extend and improve our tailor-made services especially where these can earn substantial additional revenue. The recent upsurge in interest in the causes and economic impact of climatic variations is likely to continue and to call for increased climatological advice and research into possible natural and man-made climatic changes.

Increasing concern with the environment is likely to require more work on the transport and transformation of pollutants in the atmosphere including studies of their sources and sinks. The need to improve agricultural output and productivity should lead to greater demand for meteorological advice in connection with land use, development of new varieties, and control of crop and animal diseases. Other areas where meteorology can be expected to play a more important role are energy conservation and development of new sources, for example solar, tidal and wind power.

However, we must not be concerned solely with solving immediate problems. It is essential for the Office to maintain a strong base of knowledge and skills over practically the whole field of meteorology so that we can respond quickly and effectively to new demands and problems of national or international importance. Just as the original 10-year plan did not envisage such major developments as COMESA, METEOSAT, TIROS N instrumentation, and the demands of the offshore oil industry, so this new plan is unlikely to foresee all the new developments and demands of the next decade. It is therefore most important for the Office to maintain a strong research effort especially as no other organization in the United Kingdom or indeed in Europe can match our range of expertise and resources.

We should, in general, be ready to make these resources and skills available to any body, official or private, willing to pay for them, provided only that the work makes good scientific sense and does not detract unduly from higher-priority tasks. We should do more to publicize our expertise and to bid for environmental projects having a major meteorological content, the overall objective being to ensure that the Office makes a maximum contribution to the national economy.

Forecasting for a few days ahead

In recent years, owing largely to the introduction of objective numerical models, the accuracy of forecasts in the 24–72 hour range has substantially improved. The overall accuracy of 72 hour predictions of surface weather is now about as good as that of the 48 hour predictions of ten years ago, and the 48 hour forecasts are now about as good as the 24 hour forecasts were then. Moreover the number of serious errors in the 24 hour forecasts (synoptic reviews) has been halved from about 13 per cent to 6 per cent whilst the proportion of 'A' markings has increased from about 50 per cent to 70 per cent.

However, there is still room for considerable improvement in the accuracy and detail of forecasts for several days ahead and this will continue to merit a substantial effort in the improvement of the models and of the observational data base. This, and the hope of extending useful numerical predictions up to a week or more ahead, are the main reasons for our substantial contributions to the First GARP Global Experiment (FGGE). Incorporation of the FGGE data into the best models that we can produce by 1980 should provide a fairly firm indication of the practical limits to atmospheric predictability and of both the minimal and optimal designs of a global observing network.

The Office is committed to processing the FGGE synoptic data for the European and African areas, to providing global stratospheric analyses, and to contributing to the new observing systems through METEOSAT and TIROS N.

Beyond 1980 our work on medium-range forecasting will have to be closely

co-ordinated with that of the European Centre for Medium-range Weather Forecasts (ECMWF) which should be operational in mid-1979.

If the Centre is successful in its main aim of producing numerical forecasts for 4–10 days ahead, some major reorganization and changes in our forecasting operations may be necessary to avoid duplication of effort. However, this is not likely to arise before the mid-1980s; meanwhile the Office should press ahead with its program of medium-range forecasting until it becomes apparent that ECMWF can do the job at least as well as the Office. The potential value of reliable medium-range forecasts to such weather-sensitive industries as agriculture, building and construction, energy, offshore operations, and even to the armed services for tactical planning, is so large that we cannot opt out until the success and future of ECMWF are assured.

Short-range forecasting

Although dynamical models have produced noticeable improvements in the accuracy of forecasts for 24–72 hours ahead, they have done little to improve the accuracy of predictions of surface weather, especially of the timing, duration and intensity of precipitation, over the first 12 hours. The general public and some industries (for example agriculture, gas and electricity) require greater accuracy and detail than we currently provide for a few hours ahead when the weather is often dominated by mesoscale and small-scale systems which cannot be represented explicitly in current models. Although higher-resolution models are being developed and merit a good deal of effort, it seems that for the next few years practical improvements are more likely to result from the extrapolation of the movement and development of precipitation patterns observed by radar and high-resolution satellite pictures.

The Chester-Dee experiment has established that rainfall over an area of radius of about 100 km can be measured not only continuously and in real time but more accurately by a single radar than by an economically feasible network of automatic rain-gauges. A linked network of about 12 radars might therefore provide continuous measurement of rainfall across the whole country and, at the same time, a complete storm detection and tracking system that could form the basis of a short-range forecasting service.

An experimental mini-network of three radars is now being installed at Camborne, Clee Hill and Upavon. The digitized output of the three radars will be composited to form a single rainfall map with rainfall intensities shown in eight colours on a television screen that can be updated every few minutes. The output may be transmitted by telephone line to any forecast office and in the first instance will be received in the Main Meteorological Office at Gloucester where a special short-range forecasting unit will be established to exploit the technique in conjunction with satellite pictures (half-hourly pictures from METEOSAT and very-high-resolution pictures from NOAA orbiting satellites) received at Lasham. This experimental network is expected to be operational in April 1978; later it may be extended to incorporate radars in the Thames Valley (covering London) and at Shannon and in Jersey.

A few years' trials should demonstrate the value of such a service, after which we contemplate a national network, jointly funded by a number of organizations including the Office, and based on a new set of unmanned radars, the first of which is now being ordered by the North West Water Authority primarily to help in the regulation of dams and reservoirs and in flood control.

Studies of changes in temperature, humidity and wind associated with the development and passage of mesoscale weather systems, aided by a closer network of automatic stations, may also lead to improved short-range forecasts of temperature and wind which, from many points of view, for example consumption and conservation of energy, are more important than precipitation forecasts.

An important requirement of such a short-range warning and prediction system will be the rapid dissemination of these 'perishable' data to the customer and here we look forward to utilizing such systems as Viewdata and Ceefax. We are actively collaborating with the Post Office in the use of Viewdata for this purpose and hope that this will be a significant source of revenue. Besides providing an operational service, the radar/satellite system should provide much valuable data for research on the structure and development of mesoscale systems and input for new dynamical models.

Long-range forecasting

The present long-range forecasts, of which about two-thirds show some positive skill, appear to have reached a plateau in performance and there seems little prospect of a substantial improvement by continued application of the present empirical, largely analogue, methods. Research will continue with the object of refining the selection of analogues and other predictors and increased attention will be given to the production of seasonal forecasts which are probably not much more difficult or much less accurate than the monthly predictions.

However, in the longer term, we must look to dynamical methods for future progress where we have some reason to believe that the outputs of numerical models, perhaps averaged over several days, will provide a better guide to the general trends of the weather over weeks and months. Forecasts based on this approach are likely to require large amounts of computer time; they might, for example, call for several integrations to 50 days each week to determine those features that can be considered 'stable'. Experiments to assess long-range forecasts on this basis are now in progress and will form part of the case for more powerful computing facilities. They could lead to the introduction of operational forecasts by 1980.

Specialized services for industry

Every effort should be made to expand and improve our specialized services to industry, the public utilities and commerce and thereby make a maximum contribution to the national economy and to increase our revenue. The Office has become more commercially minded and cost-conscious in recent years and has increased its revenue from £2 million in 1969/70 to an estimated £8·7 million for the current year, an increase from 21 per cent to 30 per cent of gross expenditure. Among the new services introduced in recent years, the income from ship-routeing and ocean tows has increased from £6000 in 1968/69 to £66 000, from the offshore oil and gas industry from £30 000 (1969/70) to £600 000, for hydrometeorological services from only £2600 (1973) to £47 000, and for climatological services from £14 400 (1974) to £45 200. The revenue from our largest customer, civil aviation, has increased from £1·5 million (1971/72) to £6·8 million.

The main problem is how to maximize revenue while maintaining an adequate

and basically free service which the public has always had and will continue to demand. Within the constraints of a government department providing a public service, which are more limiting than those of a wholly commercial organization, we must become more aggressive in marketing our wide range of services and expertise and convince potential customers of the benefits of paying for a tailor-made service compared with the free but less specific and detailed advice available through the mass media. We must also show that we can provide a better service than the private consultants who have gained a foothold in some areas, in some cases by using our data and forecasts. In order to be fully competitive the Office's much greater expertise and facilities may not be sufficient; we must be able to respond flexibly and quickly to urgent requests for help and have staff available at short notice to deal with emergencies and important tasks such as tows of oil-rigs, environmental accidents, profitable overseas consultancies and so on.

Although the Office has the lion's share of the market in forecasting for the offshore industry, providing services for some 50 sites, there is still scope for expansion. The demand for ship-routeing has failed to grow as fast as we had hoped, largely because of the fall in North Atlantic traffic. However, it should be possible, through aggressive marketing and competition with commercial agencies, to build and maintain this service at the level of at least 300 routeings a year. This, together with the increasing income from the long-distance tows of oil-rigs and platforms, should keep the service financially viable. There have also been several recent requests for weather forecasts and advice on climatological trends in distant parts of the world in connection with the production of valuable crops such as cocoa and coffee; the fact that we have operational atmospheric models and are developing global models may enable us to give such advice which is not generally available elsewhere in the world.

In summary, we should be ready to bring our resources and expertise to bear on any problem of economic importance if the customer is willing to pay the full cost. Diversification into new fields will also be prudent in order to offset a possible drop in demand for services from our traditional customers such as civil aviation, which is becoming less weather-sensitive. However, given that the Office is obliged to provide a basic free public service, the scope for increased 'commercial' business is likely to remain rather limited and it is unrealistic to expect that our revenue in real terms will increase rapidly and make the Office anywhere near self-supporting.

Research

In the main, the research program should continue along the same general lines as at present with some modest expansion during the next decade for the reasons that follow. But, in common with scientific research in the country as a whole, the overall expansion is likely to be small compared with that of the last decade. So, if we are to tackle new problems and seize new opportunities, it will continually be necessary to review priorities and to be ready to curtail outmoded or less promising projects in order to support new growth areas. However, the central problems of meteorology still await solution and so the basic pattern of our research is not likely to undergo drastic changes though there may well be changes of emphasis and priority from time to time.

A continuing high level of research into basic atmospheric dynamics and numerical weather prediction will be required to meet the demand for weather forecasts of greater accuracy and range discussed earlier. More emphasis will be given to the study of mesoscale systems which are likely to be of dominant importance in short-range forecasts. We should also devote more effort to long-range forecasting on a monthly/seasonal time-scale, especially to the development of dynamical methods in the hope that these may eventually replace the current empirical and largely subjective techniques. Further improvement of 1 to 10 day predictions will depend not only on the development of better numerical models with better representation of the physical processes such as cloud and radiation, but on better (global) observations and, in the limit, by the inherent predictability of the atmosphere on these time-scales.

Concern with the environment and the possible effects of man-made activities on weather and climate is likely to persist and to become of increasing political and economic importance. The Office should therefore give increased attention to understanding the physical basis of climate and to developing models to simulate, and perhaps eventually to predict, climate changes both natural and man-made. This will almost certainly necessitate greater attention to the interaction between the oceans and the atmosphere and the development of joint atmospheric–oceanic models. This will require some considerable expansion of the Dynamical Climatology Branch.

All weather and climate models need better representations of transfer processes in the atmospheric boundary layer, a better understanding of which is also essential to the elucidation and prediction of transport and transformation of pollutants in the atmosphere and the oceans. A larger scientific effort in this field, especially in the Boundary Layer Research Branch, is indicated.

An increased effort to observe, model and predict the dynamics and chemistry of the stratosphere and lower mesosphere will be required to assess the risks to the ozonosphere from various man-made chemical compounds—another issue which is not likely to die away quickly.

A new Branch or group is planned to study the dynamics and chemistry of the stratosphere and mesosphere, building on the expertise gained during the highly successful COMESA project. The monitoring of active chemical species in the high atmosphere is likely to be a continuing requirement. If the satellite radiometer now being built by the Oxford University group for flight on NIMBUS 6 in 1978 proves suitable for this purpose, the Office might contemplate developing operational versions of this instrument for long-term global monitoring, perhaps in collaboration with the USA.

The numerical prediction of the sea-state, especially of waves and swell, will be of increasing importance and value to the offshore industry and for the routeing of ships and long-distance tows of oil-rigs. The development of a suitable model, linked to our fine-mesh atmospheric model, is likely to become an operational requirement in the near future.

The evolution of both military and civil aircraft is likely to present new meteorological problems and to resurrect some old ones, for example fog, low-level turbulence, low-level wind shear and helicopter icing, and we must try to anticipate these well in advance of the operational requirement.

There is room for the Office to make a much greater contribution to agriculture, the most important and one of the largest of our industries. Although we have had notable successes, for example in the prediction of crop and animal

diseases, there must be much greater scope for assisting this highly weather-sensitive industry with a total production exceeding £3 thousand million. This may require a good deal of missionary and educational work on our part.

An increased program of global modelling for both extended weather forecasting and climate simulation, together with our investment and interest in GATE, will require an expanded effort in tropical meteorology. Our initial success in developing an operational tropical forecasting model for GATE might well be exploited to produce daily forecasts for certain tropical regions such as Africa for which additional observations will be supplied by METEOSAT. Interest in such forecasts is already being expressed by UK companies trading in such volatile and expensive commodities as cocoa and coffee.

Only the Meteorological Office, outside the United States, has the facilities, scientific manpower and expertise to tackle many of these problems on a scale sufficient to make real progress and to provide a judgement, independent of the USA, on many of the controversial and politically sensitive issues mentioned above. This, together with the economic and social value of improved weather advice and other meteorological information, is likely to provide continued firm support for our research program whilst the high quality of our young scientists should guarantee its continued success.

New facilities

(a) *Observations.* In considering new or improved facilities that will be required to fulfil the above objectives, first attention should be given to an adequate observational data base without which major investment in new models and more powerful computers may be partially nullified.

Starting with the UK observational network, the present coverage of synoptic surface stations, considerably reduced over the years by RAF closures, has serious gaps which will have to be filled mainly by automatic weather stations as envisaged in the recent review by the working group on UK networks. The nine original experimental automatic stations now being redeployed for operational use are able to make satisfactory measurements of all the synoptic parameters except cloud and present weather but the lack of cloud observations should be at least partially compensated for by the half-hourly pictures from METEOSAT and by the VHRR pictures from orbiting satellites. A further 20 stations of improved design will be installed in the next few years and up to 30 additional automatic stations, making 50–60 in all, are planned over the next ten years.

The climatological network is uneven in both distribution and quality and it is becoming increasingly difficult to rely on voluntary effort from co-operating institutions and individuals. Again automatic stations should help fill some of the gaps but finding secure sites, especially in remote areas, may be difficult.

The national rain-gauge network, consisting of some 7000 stations, also requires overhaul. A basic network of reference autographic stations should be carefully selected and maintained in consultation with the river authorities etc.; many other stations, badly sited or maintained, could probably be discontinued. Implementation of the radar rain-gauge network could make many of the stations obsolete but the basic network of telemetering rain-gauges will be required to calibrate the radars.

The long-term future of the North Atlantic Ocean Station scheme (NAOS) is likely to cause continuing difficulty and concern. The present Agreement,

despite some political problems and continual protests about rising costs, will probably hold until 1981 but beyond that the future is uncertain. Our two recently refurbished ships may last for another ten years and the same is probably true of the two French vessels. The most likely outcome beyond 1981 is that the Agreement will be extended year by year until the majority of the present ships become inoperable. There is unlikely to be enough support for the building of new ships and continuing the scheme until the end of the century. We must therefore hope that satellite techniques of remote sounding will improve sufficiently during the next decade to replace the ships' observations. However, although we can look forward to improved wind data from geostationary satellites and aircraft, the outlook for satellite temperature and humidity soundings of comparable accuracy to that of radiosonde soundings is not very promising. We may therefore have to develop a dropsonde that could be deployed from commercial and military aircraft and for which the experience gained by the Cloud Physics Branch with its system should prove most valuable.

The requirements for a global observing system, in which the Office has made a considerable investment through the establishment of several new upper-air stations overseas and by our contributions to METEOSAT and TIROS N, must await the results of FGGE. Our present commitments are likely to continue mainly by contributing to a European satellite program as described above.

(b) *Computing facilities.* The present COSMOS system, based on the IBM 360/195 and 370/158 computers, has now been in continuous 24 hour operation for over six years. It is saturated, and computing time, especially for large tasks such as global circulation modelling, has to be rationed. Implementation of the scientific program described above, in particular in numerical weather prediction and the simulation of climate, will require considerably greater computing speed and memory. A case is therefore being prepared for the Office to acquire a new high-speed processor capable of operating about five times faster than the IBM 195 in 1979/80. The European Centre for Medium-range Weather Forecasts has ordered such a machine, the CRAY 1, for delivery in mid-1978 and has an experimental prototype machine installed at the Rutherford Laboratory on which to develop its programs.

Financial approval has been obtained to upgrade the present COSMOS system by the addition of at least 1 megabyte of core storage to the IBM 195 and to enhance the IBM 158 by additional memory. This, together with the new fast 'number cruncher', would provide us with a very powerful and flexible system that should meet our requirements well into the 1980s.

(c) *Telecommunications.* On completion of Phase III of the automated telecommunication complex in mid-1978, the modernization of the central system will have been largely completed. Some further rationalization and modernization of facilities at London/Heathrow Airport and HQ Strike Command are planned and there may be scope for some extension of automation into the collecting centres.

There is an urgent requirement to replace the present analogue facsimile by faster digital methods and widespread dissemination of satellite pictures, especially of half-hourly pictures from METEOSAT and VHRR pictures from polar orbiters, will facilitate local forecasting.

(d) *Aircraft.* It will probably be necessary to replace the MRF Canberra for high-altitude research during the next decade. Servicing and maintenance

problems may arise if the Royal Air Force phase out the Canberras before we need to replace our aircraft. Modern methods of telecommunication and data processing should facilitate remote control of the flight and the instrumentation, making it possible to use a single-seat high-performance aircraft, without a meteorological observer.

Otherwise the MRF is well equipped and we can now look forward to a sustained program of measurement and investigation obtaining the scientific return on the major effort expended in recent years in equipping the Hercules and Canberra with modern instrumentation and data-processing facilities.

Scientific staff

The total complement of non-industrial staff is planned to reach 3000 by 1 April 1979 and to remain at that level for the next few years. Pressures to contain public expenditure and limit the overall size of the Civil Service are likely to prevail for several years and it will therefore be very difficult to achieve any significant growth of staff numbers unless there are very strong demands for additional meteorological services by customers willing to pay the full costs.

However, even within the limitations of a fixed overall ceiling, there should be considerable scope, by the reassessment of tasks and priorities, through continuing automation and improved efficiency, to implement some new projects and improve career and promotion prospects.

We have seen in the past few years a high rate of retirement from the more senior scientific grades and this, together with low recruitment of honours graduates in earlier years, has led to shortages, particularly at the Principal Scientific Officer level. The present age structure suggests that in future years the opportunities for recruitment and promotion of high calibre scientists will be more limited than in recent years and we should therefore attempt to promote as many of our very able young scientists as possible through the Individual Merit Scheme.

The situation for the forecasting and scientific support grades is, however, brighter than it has been for some time, with retirements likely to rise sharply in the next year or so and to remain at a high level for about ten years. In this category it will no doubt be possible to fill a high proportion of the large number of vacancies which will arise during the next decade by promotion of well-qualified staff from the junior grades, leaving the remainder to be filled by direct recruitment, preferably of graduates. In this area recruitment and promotion will undoubtedly be much healthier than in the past and the large movements of staff through these grades will give an opportunity for altering the proportion of staff working in different fields without major retraining programs or asking large numbers of staff to move to different fields against their wishes. It will also allow the recruitment of more specialists as necessary, for example in computer work or electronics.

Amongst the junior grades the career prospects, taking account of retirements and other losses, are likely to be much better than they have been for many years.

Buildings and accommodation

Since the total staff complement of the Office is not likely to increase significantly during the next few years, no major changes in Headquarters buildings and accommodation are planned.

The only significant expansion is likely to be at Beaufort Park where some small additions are required in the very near future followed by a modest extension of the present building during the next ten years.

551.574.7:629.7

THE ROLE OF METEOROLOGY IN HELICOPTER ICING PROBLEMS

By P. RYDER
(Meteorological Office, Bracknell)

SUMMARY

This report reviews the extent and nature of the problems created by helicopter icing and attempts to identify the role of the meteorologist both in their formulation and in their solution.

The physical problem is highlighted by a discussion of some of the processes involved in accretion. The operational problem is reviewed and the main features of the current motivation for helicopter icing research are sought.

No conclusion about the need for, or possibility of, improved weather forecasting is reached, but this is not identified as the most important area of concern. The task of the meteorologist in helping to formulate and constrain the problem through the application of physical understanding is emphasized. It is suggested that although an increased knowledge of hazard-creating processes must be sought as a matter of priority, there is also a need for an improved climatology of some relevant atmospheric parameters.

1. INTRODUCTION

The hazards created by icing on aircraft have been recognized in principle for many years. Key work in this country has been carried out by Hardy (1946), Messinger (1953), Best (1956) and Jones (1961) for example. The problems have been extensively studied abroad, particularly in the National Research Council of Canada by Stallabrass and co-workers. It is therefore rather surprising to discover the extent to which the icing of helicopters apparently continues to create significant operational problems. Thus, before attempting to discuss the role of atmospheric physics in contributing to possible solutions, it is highly appropriate to review the extent and nature of the problems being experienced.

2. THE PHYSICAL PROBLEM

In principle, ice may be expected to accrete on any surface which is below the frost-point of air in contact with it. However, this is a statement of thermodynamic possibility only, and the efficiency with which accretion actually occurs is not so simply defined. To gain an appreciation of some aspects of the problem, the energetics of ice accretion on a surface exposed to a moving airstream containing either liquid or solid water is reviewed. The analysis follows that of Jones (1961) and more recently of Cansdale and McNaughtan (1977). It is assumed that there is no heat transfer into or out of the structure whose surface temperature is of interest. The nomenclature is defined in the Appendix.

In the absence of liquid water or ice particles the surface will experience:

(a) a kinetic heating rate of $q_v = \dfrac{hr\ V_\infty^2}{2\ c_p}$

and

(b) a convective rate of heat loss of $q_c = h\ (t_s - t_\infty)$.

Thus at equilibrium the surface temperature may be expected to be some $rV_\infty^2/(2\ c_p)$ above the ambient value. At rotor-tip airspeeds of 200 m s^{-1} this excess may be $\approx$18 °C but in the central region of the blade this becomes $\approx$5 °C. Impacting supercooled water may be assumed to warm to 0 °C and to freeze at this temperature before cooling back to an equilibrium surface temperature if this is below 0 °C. Thus there will be:

(c) a rate of heat loss in warming the impinging water to 0 °C of

$q_w = -R_w\ c_w\ (0 - t_\infty)$

where $R_w = E\ V_\infty\ W$.

Assuming the collection efficiency $E = 1$, $V_\infty = 100$ m s^{-1} and $W = 0{\cdot}5$ g m^{-3} and an ambient temperature of -10 °C, $q_w = -2{\cdot}2$ kW m^{-2}.

(d) a heat gain due to the release of latent heat on freezing this water, at a rate given by:

$q_f = R_w\ L_f = E\ V_\infty\ WL_f \approx 16$ kW m^{-2} in the above example.

(e) a sensible heat gain in cooling the accreted ice from 0 °C down to t_s of

$q_i = R_w\ c_i\ (0 - t_s) = 0{\cdot}5$ kW m^{-2} if $t_s = -5$ °C.

Additionally there will be:

(f) a heat gain due to the kinetic energy of impinging water or ice. Note that accretion is not necessary for this to be experienced. Thus:

$q_k = R_w'\ V_\infty^2/2$, where $R_w' = E_c\ V_\infty\ W$.

Therefore

$q_k = E_c W\ V_\infty^3/2$.

For $W = 0{\cdot}5$ g m^{-3}, $V_\infty = 100$ m s^{-1}, $E_c = 1$, $q_k = 0{\cdot}25$ kW m^{-2} but for $V_\infty = 200$ m s^{-1}, $q_k = 2$ kW m^{-2}, a far from negligible contribution.

(g) a rate of heat loss from the surface because of evaporation or sublimation. Thus:

$$q_e = 0{\cdot}622\ \frac{L_e\ h}{c_p}\ \frac{e_{sw} - e_\infty}{P_\infty}$$

$$q_s = 0{\cdot}622\ \frac{L_s\ h}{c_p}\ \frac{e_{si} - e_\infty}{P_\infty}$$

depending upon t_s. It is not always obvious which expression should be used but fortunately the difference between them is normally much less than either. For an object of $\approx$10 cm diameter, whose surface temperature is -5 °C, moving

with a velocity of 100 m s^{-1} relative to an airstream of -10 °C, there will be a rate of heat loss due to evaporation or sublimation of $\approx 0{\cdot}4$ kW m^{-2}. This may be compared with a simultaneous convective rate of heat loss of ≈ 1 kW m^{-2}.

The above review demonstrates that there are a number of terms which, at typical rotor airspeeds and liquid water content, create heating or cooling rates of the order of 1 kW m^{-2}. However, the latent heat term has a dominant effect down to quite low water contents. An important corollary of this is that the thermal effectiveness of accreted particles is crucially dependent upon the phase of water substance from which they are formed. Quite low concentrations of either phase in the presence of significant quantities of the other can have a profound effect upon whether or not ice is accreted.

The situation is further complicated by proper consideration of the collection efficiency, E, so readily assumed above to be unity. In fact, the collection efficiency is itself the product of a collision efficiency E_c (the probability that a collision will occur between a surface element and a drop or ice particle) and an accretion efficiency, E_a (the probability that the surface will retain the mass of the drop or ice particle). If run-back is neglected (see below) it is probably safe to assume that $E_a = 1$ for water drops. This is certainly not so for ice particles, whose adhesion is dependent in an essentially unknown manner upon the amount of liquid on the surface. The collision efficiency, E_c, is a function of the inertial and viscous forces acting upon the particle. Langmuir and Blodgett (1946) considered this problem in relation to drops colliding with cylinders. It is inappropriate to consider the detail of their results and those of later workers who studied more representative airfoil shapes, for example Brun (1957) except to note that, in general, the smaller the particle and the larger the characteristic dimension of the collecting object the smaller is the collection efficiency. In addition it is important to recognize that for drops in the range 10 to 30 μm diameter and (for example) cylinder diameters in the range of a few centimetres to a metre, the collection efficiency is a sensitive function of these dimensions. It is unfortunate that these ranges include that part of the cloud droplet spectrum containing a significant fraction of the total water content and the scale size of aerodynamically sensitive structures.

Finally, the problem of water run-back and of the rate of cooling and mass accretion (not simply equilibrium values) create a further level of difficulty by controlling the form and strength of the accreting ice. Such problems are most unlikely to yield to any formal analysis and will probably be resolved, if at all, by empirical methods.

3. The operational problem

This centres around the need to achieve a required aviation activity at an acceptable level of risk. The risks are created by a number of hazards. Even if the amount of icing were entirely predictable, various structures differ in both their catch efficiency and their ability to withstand this accretion whilst fulfilling their aviation role. It is reasonable to expect that a given helicopter type will be sensitive to a range of hazards created by icing on the airframe, engine intake, rotor blades, windscreen etc., that different helicopter types will experience problems to differing degrees in these areas and that, although some aspects of icing are likely to be common to both fixed and rotary wing aircraft, there are likely to be significant differences also.

The basic approach employed at present is that of avoiding risk by prohibiting

flight in atmospheric conditions which could cause hazard. Implementation of the policy is of course fraught with practical difficulty. There is an implication that hazardous conditions can be specified *and* forecast with sufficient accuracy to maintain a useful operational 'window'. It is the pressure of these practicalities which manifest themselves as the current level of interest in the basic problem. There is a measure of urgency created by the military role of helicopters, particularly at sea in the anti-submarine role. Such an interest is historically very natural for the United Kingdom but this has been strengthened by the growing economic significance of the North Sea area. The pressures arising from the civil use of helicopters also owe part of their origin to the need to supply the North Sea oil industry. In any event, it is very natural that both civilian and military users seek the maximum possible operational window. This in turn implies that forecasting of hazardous conditions, in the sense of generating warnings of hazardous areas at specific times, can only be an interim measure. Opinions differ on the extent to which improvements in such forecasts are necessary or indeed possible at present. The long-term aim of military operators at least, is to seek an all-weather capability. Thus the fundamental operational requirement is for data from which hazards can be predicted, protection systems designed and the widest possible cost-effective clearances be given. The question of improved forecasting is considered again below.

4. Current position

The methodology adopted hitherto in the United Kingdom, in response to this fundamental requirement, has centred around the trials concept of exposing helicopters to presumed hazardous conditions and observing the ensuing effects. The aim is to discover both the vulnerability of the specific, perhaps partly protected, helicopter and to define the atmospheric conditions which are causing problems. Most of these trials have been undertaken in the free atmosphere with and without attempts to modify the test environment through the use of spray rigs. However, some controlled experiments on specific items, under simulated conditions, have been attempted in so-called icing wind tunnels for example. The free atmosphere trial implies excellent instrumentation on the helicopter to monitor the creation of hazards and to define the specific meteorological conditions causing them. The lack of control over the environment also requires a long sequence of trials to sample the possible range of variables. When it is realized that, even today, there is almost a complete lack of adequate instrumentation to measure accretion rates and that the helicopter is far from an ideal vehicle for making free atmospheric measurements, it is not too surprising that very little physical insight into the fundamental problems has been achieved by this approach. When these difficulties are combined with the logistic problems of operating the trials technique, often outside the United Kingdom, with the full range of helicopters in service and under development, whilst trying at the same time to assess various de-icing or anti-icing techniques, it is surprising that *any* progress has been made on the typical time-scale of aircraft procurement to obsolescence. Perhaps this is reflected in the limited 'clearances to fly' in icing conditions which have been achieved so far.

The wind tunnel trial implies that the range of atmospheric variables in combination can be specified and created well enough to allow representative simulation. Unfortunately, without adequate guidance from free atmosphere

experiments and data, this begs the question and preoccupation with introspective experiments, having little to do with real problems, is a distinct possibility.

Nevertheless, if progress is to be made in understanding the processes by which ice accretion actually causes hazards it must be through proper application of the above methods. The atmospheric scientist has hitherto tended to respond to specific queries from those concerned with the helicopter icing problems, often with an inadequate notion of the basic problem and an uncertainty about whether or not the query is correctly formulated. There is evidence of this in the lack of agreement over the possibility of improved forecasting methods, for example.

Finally, in returning to the question identified in the introduction, the motivation for the particular concern in helicopter icing at present has its roots in

(a) both the military and civil need for the widest possible operational capability in areas whose climates are likely to create hazardous conditions;

(b) the fact that helicopters spend a very significant fraction of their flying time in a region of the atmosphere where temperature and water content are likely to lead to hazardous conditions;

(c) the fact that compared with fixed wing aircraft the lifting surfaces on a helicopter are expected to function across a much broader spectrum of aerodynamic conditions (e.g. airspeed and angle of attack). These create at one extreme the possibility of a high rate and efficiency of water catch per unit chord distance and, at the other, a 'close to stall' state. The complexity of rotor support and control gear also make it difficult, expensive and likely to create significant weight penalties, to provide anti-icing or de-icing facilities. The helicopter is an intrinsically vulnerable aircraft which it is difficult to protect by conventional means;

(d) the fact that helicopters can, and occasionally must, remain in a rather closely defined geographic location. In doing so, they become sensitive to a scale of atmospheric inhomogenity which has not received the same attention as the synoptic scale for example and which is certainly very difficult, if not impossible to forecast.

5. The role of the meteorologist

The designer of helicopters, and those creating protection systems and assessing their ensuing operational role, are concerned to know the probability of a particular hazard being experienced at a given place and time. Thus a typical hazard might be an unacceptable increase in the torque necessary to achieve a required lift on a Sea King helicopter, in the vicinity of say 60°N, 0°W, in January. The probability of this occurring must itself be the product of the probability that the hazard will result from particular meteorological conditions and the probability that such conditions will exist at the required position and time. The problem of defining these probabilities contains meteorological and engineering components, which are intimately connected. The meteorologist may reasonably expect that the atmospheric parameters whose climatology is required be clearly specified. The engineer may reasonably expect that those parameters which are likely to be experienced be identified so that he may determine their icing effect.

The meteorologist, with some justification, will argue that the broad envelope

of conditions which are likely to create hazards can be (indeed have been) identified. However, the difficulty of discovering the actual physical basis of the creation of icing hazards continually creates pressure for refinement of this envelope. There is little doubt that some refinement is possible, perhaps not through the provision of more detailed statistics, but by applying accepted physical understanding to the problem. Hence the first role of the atmospheric physicist is likely to be interpretative. A few examples serve to illustrate the approach:

(1) In section 2, the thermal importance of mixtures of ice and water was identified. However, thermally significant mixtures may have a very limited, transient occurrence in the real atmosphere because of the supersaturation experienced by ice particles in the presence of water drops below 0 °C.

Quantitative arguments of this type are unlikely to demonstrate that all atmospheric occurrences of ice and liquid water have a low probability (snow falling through supercooled cloud may not be in equilibrium, for example). However, the potential simplification certainly justifies a numerical study of the problem.

(2) Calculations of the maximum free water content of ascending air (see Ludlam (1957) for example) together with a crude climatology of surface temperature, could be used to create a useful upper bound for cloud water content. This idea was briefly discussed by Jones (1961) but so far as is known has not been used in the way suggested.

There is a fundamental requirement that progress must be made in understanding the physics of hazard creation. This will not be achieved until instruments are available to observe and quantify the icing process and the co-existing state of the atmosphere. The atmospheric physicist may reasonably expect to contribute to this required development. Recent improvements in drop sizing instrumentation (Knollenberg, 1976 are likely to assist here.

It may reasonably be argued that any attempts to define a climatology of icing parameters more closely must await their full recognition. For example, it may be that drops of diameter greater than say 25 μm play a crucial role in rotor blade icing because of the much reduced collection efficiency experienced by smaller sizes. If this supposition was in fact found to be correct, it would certainly have a significant effect on a study aimed at defining the incidence of icing hazards. Nevertheless, although the timing of a study is open to question, there is little doubt that an improved definition of the probability of occurrence of various combinations of atmospheric variables will ultimately be necessary. It has been suggested that if such a study is undertaken more or less in parallel with a properly instrumented study of hazard-creating processes, this will create the most cost-effective solution.

It is important to recognize here that the climatology of interest is unlikely to be of the commonly measured meteorological variables alone. At first sight the task of defining the climatology of, say, liquid water content as a function of temperature, altitude, geographical position and time of year is a horrendous, if not impossible one. Almost certainly an approach which seeks to separate the problem into climatological and interpretative components will be necessary. Thus, it is suggested that existing synoptic data be used to define the probability of occurrence of, for example, cloud type and amount, cloud base height, and surface temperature over the region of interest and that the relationship between

these and icing parameters be established separately. An understanding of the physics of water substance in the atmosphere will be an essential ingredient in such a solution, of course, but there is no doubt that currently available atmospheric data are inadequate to meet the latter task. The source of the information required is expected to be a mixture of existing data, new measurements obtained on a dedicated and properly instrumented aircraft such as the MRF C-130, and measurements obtained through the use of precipitation radar and satellite imagery.

Any attempt to improve forecasting techniques must be preceded by a clearer understanding of present deficiencies and the nature of realistic future improvements. There is little doubt that attempts to improve synoptic scale temperature and atmospheric water content predictions could be made but whether or not this would fill a real need is far from clear. As with the atmospheric study program described above, perhaps the greatest single contribution that the meteorologist can make to the problem is that of helping to formulate the questions as well as the answers.

References

BEST, A. C. 1956 Ice accretion on aircraft in warm-front conditions. *Met Mag*, **85**, pp. 257–263.

BRUN, E. A. 1957 Icing problems and recommended solutions. North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development. *AGARDograph* No. 16.

CANSDALE, J. T. and MCNAUGHTAN, I. I. 1977 Calculation of surface temperature and ice accretion rate in a mixed water droplet/ice crystal cloud. Farnborough, Royal Aircraft Establishment. *Technical Report* 77090.

HARDY, J. K. 1946 Protection of aircraft against ice. Farnborough, Royal Aircraft Establishment. *Report* No. S.M.E. 3380.

JONES, R. F. 1961 Ice formation on aircraft. Geneva, World Meteorological Organization. *Technical Note* No. 39.

KNOLLENBERG, R. G. 1976 Three new instruments for cloud physics measurements: the 2-D spectrometer, the forward scattering spectrometer probe, and the active scattering aerosol spectrometer. Boston, Mass., American Meteorological Society. *International Cloud Physics Conference, July 1976, Boulder, Colorado*, pp. 554–561.

LANGMUIR, I. and BLODGETT, K. B. 1946 A mathematical investigation of water droplet trajectories. Wright Field, Dayton (Ohio), U.S.A.A.F. Air Materiel Command, *A.A.F. Technical Report* 5418.

LUDLAM, F. H. 1957 Introduction to the first edition of 'The physics of clouds' by B. J. Mason (London, Oxford University Press).

MESSINGER, B. L. 1953 Equilibrium temperature of an unheated surface as a function of airspeed. *J Aero Sci*, **20**, pp. 29–42.

APPENDIX

c_p = specific heat of air at constant pressure $= 1005\ \mathrm{J\ kg^{-1}\ K^{-1}}$
c_w = specific heat of water $\approx 4{\cdot}2 \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}$
E = particle collection efficiency
E_c = particle collision efficiency
E_a = accretion efficiency
D = cylinder diameter
e_{sw} = vapour pressure over water at t_s
e_{si} = vapour pressure over ice at t_s
e_∞ = vapour pressure of free atmosphere
h = convective heat transfer coefficient
k_a = thermal conductivity of air $\approx 2{\cdot}4 \times 10^{-2}\ \mathrm{W\ m^{-1}\ K^{-1}}$
L_e = latent heat of evaporation $\approx 2{\cdot}5 \times 10^6\ \mathrm{J\ kg^{-1}}$
L_f = latent heat of fusion $\approx 3{\cdot}3 \times 10^5\ \mathrm{J\ kg^{-1}}$
L_s = latent heat of sublimation $\approx 2{\cdot}8 \times 10^6\ \mathrm{J\ kg^{-1}}$
Nu = Nusselt number $= hD/k_a$
P_∞ = free atmosphere pressure
q = rate of heat transfer per unit area
r = recovery factor
Re = Reynolds number $= \dfrac{\rho_a V_\infty D}{\mu_a}$
R_w = rate of water mass caught per unit area
R_w' = rate of water mass impinging per unit area
t_s = icing surface temperature
t_∞ = free atmosphere temperature
V_∞ = free atmosphere velocity
W = mass concentration of water in the air
μ_a = viscosity of air $\approx 1{\cdot}7 \times 10^{-5}\ \mathrm{kg\ m^{-1}\ s^{-1}}$
ρ_a = density of air $\approx 1{\cdot}2\ \mathrm{kg\ m^{-3}}$

An approximate value of h is obtained by assuming with Hardy (1946) that at stagnation the Nusselt number and the Reynolds number are related by

$$Nu = (Re)^{\frac{1}{2}}$$

hence

$$h = k_a\left(\frac{V_\infty \rho_a}{D\ \mu_a}\right)^{\frac{1}{2}}.$$

For the purpose of the budget calculations carried out in section 2, it is assumed that this stagnation value is representative of the whole body.

For $V_\infty = 100\ \mathrm{m\ s^{-1}}$, $\rho_a = 1{\cdot}2\ \mathrm{kg\ m^{-3}}$, $D = 10\ \mathrm{cm}$, $\mu_a = 1{\cdot}7 \times 10^{-5}\ \mathrm{kg\ m^{-1}\ s^{-1}}$, and $k_a = 2{\cdot}4 \times 10^{-2}\ \mathrm{W\ m^{-1}\ K^{-1}}$ i.e. representative of surface air at $\approx 0\ ^\circ\mathrm{C}$, $h = 200\ \mathrm{W\ m^{-2}\ K^{-1}}$.

The so-called recovery factor, representing the influence of a cylinder on free stream values of V_∞ for example, has been assumed to be $\approx 0{\cdot}9$ for budgetary purposes.

551.583:061.4

THE 'EXPLORATION' EXHIBITION AT THE SCIENCE MUSEUM

'Exploring Our Changing Climate' by Tom Williamson (HMSO, 1977)

By R. P. W. LEWIS
(Meteorological Office, Bracknell)

On 16 December 1977 a new major exhibition based on the theme of 'Exploration' opened at the Science Museum in South Kensington; it is expected to run for at least three years. There are six sections: Remote Sensing, Medical Science, Underwater Exploration, Man on the Moon, The Planets and Beyond, and—of most immediate professional interest to meteorologists—Our Changing Climate. The standard of presentation is of the usual high metropolitan quality with superbly arranged exhibits and show-cases, working models and demonstrations, audio-visual displays, and apparatus and instruments (for example the

Apollo 10 Spacecraft) that have actually been used in many of the investigations described. The booklet by Tom Williamson, a member of the Science Museum staff, is one of six published simultaneously in connection with the exhibition which are on sale in the Museum; it is excellently produced, with text and pictures—many of which are in colour—skilfully blended together. (The Meteorological Office has not been involved with either the exhibition or the booklet.)

The booklet gives what is on the whole a reasonably fair presentation of what is now known, or at least suspected, to be the way in which 'climate' has changed in the past and may possibly change in the future. It is, however, remarkable that nowhere is any attempt made to define or even to explain the terms 'climate' or 'climate change', or to distinguish the latter from ordinary year-to-year fluctuations. All the evidence for climatic change in the remote past—and indeed much in the comparatively recent past—is indirect and derived from geological and biological observations such as lake levels, the thicknesses of varves, concentration of fossil pollen-types and so on. The rates of growth and deposition, or indeed the very existence, of different living species will depend on different combinations of factors only some of which are meteorological, and the meteorological factors are themselves likely to be different for each species. Possible examples are maximum temperatures at certain seasons of the year, threshold values of rainfall or humidity, and mean annual and seasonal mean values of temperature, rainfall and sunshine; the periods over which such critical values are significant will also be different for each species and will be related to the life and reproductive cycle of that species. Furthermore, biological evolution will have taken place on the longer time-scales leading to alterations in response. It is thus obvious that 'climate change' as represented by the record of abundance of one species, or by the structure of the rings from one tree, will be different—perhaps very different—from that represented by records from another species, and neither may bear any obvious relation to changes in a simple 30- or 100-year mean of temperature. As a leading agricultural meteorologist remarked during a recent meeting of the Royal Meteorological Society, even when we know actual values of temperature, rainfall and sunshine, it is difficult if not impossible to predict the growth of a plant to any high degree of accuracy, so that to attempt to reverse the process is even more speculative. Much work is of course being done to refine the various 'proxy-data' methods, but visitors to the exhibition are not made sufficiently aware of the uncertainties of current knowledge. For example, one exhibit, and one section of the booklet, deal with the alleged evidence for climatic fluctuations in England of the growth and decline of viticulture since the time of the Romans (who introduced the vine). This topic is discussed by Barty-King (1977) who is of the opinion that social and economic factors were of much greater importance than the suggested variations in climate, and that evidence for the latter is negligible.

Prominence is given to oxygen isotope analysis as applied to the annual layers of wood in trees, ice-cores from Greenland and the Antarctic, and cores of deep-sea sediment. However, just because something is measured to a very high degree of precision by means of advanced laboratory techniques, it does not follow that deductions made from the measurements are equally precise or even valid; unless the assumptions in the chain of reasoning are fully explained, and the weak links discussed, then the ignorant visitor is merely being 'blinded by science'.

(The empirical evidence for relating fluctuations in ^{18}O concentration to a

plausible measure of climate such as a long-period mean of surface or tropospheric temperature is not very extensive and shows substantial scatter. Thermodynamical arguments applied to the formation of liquid water in rain cannot be made precisely quantitative because of the complexity of, and essential lack of equilibrium in, the processes involved.)

One of the more impressive exhibits demonstrates the effect of fluctuations in the parameters of the earth's orbit round the Sun on the distribution in space and time of solar radiation incident on the earth; these parameters comprise eccentricity, longitude of perihelion, and obliquity of the axis of rotation. The relationship of these fluctuations to the Milankovitch theory of climatic change is clearly explained. This theory is, however, described in the booklet as 'now . . . firmly established as the main reason for the comings and goings of the ice during the last 3,000,000 years' in the light of the paper published in *Science* by Hays *et alii* (1976). A caption to one of the exhibits states 'Recent studies of heavy oxygen in shells from the ocean floor have substantiated the Milankovitch theory of climatic change'. This paper does indeed adduce new evidence in favour of the Milankovitch theory (at least for the last 500 000 years!) but to describe the theory as 'firmly established' rather overstates the case. Proxy-data such as those considered by Hays *et alii* require rather involved treatment to convert them into a temperature record, and there are bound to be uncertainties of unknown magnitude in the estimated temperature fluctuations and—more important—in the regularity of the time-scale for which assumptions about the rate of deposition of deep-sea sediments have to be made. The statistical methods employed by the authors are also open to criticism (Evans and Freeland, 1977; Ross, 1978).

Most of the captions to the displays in the exhibition are taken from the booklet. Sometimes they have been taken out of context and, deprived of some of the explanations and qualifications surrounding them, are made to appear unduly sensational. An example is to be found in the announcement in very large letters over the entrance: 'The long-term future of our climate can now be predicted. It is a bleak one'.

The list of titles for 'further reading' at the end of the booklet could be improved. Books of dubious scientific value such as 'The Weather Machine' by Nigel Calder are recommended as well as what is probably the best available recent review of the subject, viz. 'Understanding Climatic Change—a Program of Action' published by the US National Academy of Sciences.

Nature and *New Scientist* are recommended as containing articles of technical interest, but no mention is made of any journal specializing in meteorology or climatology. The Symons Memorial Lecture by Mason (1976) could also well have been alluded to.

References

BARTY-KING, H.	1977	A tradition of English wine. Oxford, Oxford Illustrated Press.
EVANS, D. L. and FREELAND, H. J.	1977	Variations in the Earth's orbit: Parameter of the Ice Ages? *Science*, **198**, pp. 528–529.
HAYS, J. D., IMBRIE, J. and SHACKLETON, N. J.	1976	Variations in the Earth's orbit: Parameter of the Ice Ages. *Science*, **194**, pp. 1121–1132.
MASON, B. J.	1976	Towards the understanding and prediction of climatic variations. *Q J R Met Soc*, **102**, pp. 473–498.
ROSS, G. H.	1978	Comments on 'Variations in the Earth's orbit' by Hays *et alii*. Unpublished typescript, Meteorological Office, Bracknell.

REVIEWS

Introduction to the mathematics of inversion in remote sensing and indirect measurements, by S. Twomey. 245 mm × 165 mm, pp. x + 243, *illus.* Elsevier Scientific Publishing Company, Amsterdam, 1977. Price: US $65.

The technique of remote sensing is becoming increasingly important throughout science and particularly in meteorology, owing to the great improvement in the volume and geographical coverage of data provided by weather satellites. These measure the radiation emitted by the earth in narrow spectral bands, and the recovery of information on the vertical profiles of temperature, humidity, liquid water content etc. is achieved through the mathematical process of inversion. Until the advent of the high-speed computer, numerical solutions to many inversion problems proved intractable, and although the underlying algebra was understood, the difficulties associated with obtaining a numerical solution were not fully appreciated. Recently, however, numerical inversion methods have received a great deal of attention, and have been used operationally to produce, for example, vertical temperature soundings of the atmosphere.

In this book the author examines the mathematics of inversion methods in detail, starting from basic principles, and discusses various mathematical topics which are fundamental to the inversion problem.

He begins by describing the inversion problem and shows that many varied physical processes fall within the framework of the mathematics of inversion. Some mathematical topics which are essential for an understanding of inversion are then introduced. These topics include matrix algebra, quadrature techniques, eigenvalues and eigenvectors, the concepts of orthogonality and norms, and geometical aspects of functions and matrices.

The inversion problem itself is next examined, with the author illustrating its inherent instability. This instability arises since, in the presence of measurement errors, measured functions differing only slightly from one another could have been produced by source functions differing vastly from one another. It is shown that this instability is inherent in the problem itself and is not a consequence of approximating the integral equations which are typically encountered in inversion problems by means of quadrature formulae, and is not a consequence of computer round-off during the calculation. The author shows how the application of suitable constraints on the solution can combat the instability, giving advice on how to choose appropriate constraints and how to apply them to the inversion procedure. These constraints are of course external to the problem and so it is shown how the production of a reasonable solution depends to some extent on the constraints chosen. Finally the topics of error analysis and the information content of indirect sensing measurements are discussed, and their relationship with the inversion problems examined.

This book succeeds in filling a gap in the literature since most material published on the subject tends to be rather specialized in its application, while Twomey has gathered material which was previously scattered throughout many fields. The book has been aimed primarily at students on courses on remote sensing and satellite studies, although the research worker should also find it instructive. It should help him to see his problem in the context of the underlying mathematics, and remind him of the instability of the basic problem and the arbitrariness of the constraints he employs to overcome it.

My one small criticism of the book is that I would like to have seen at least one actual physical problem examined in detail numerically, perhaps in an appendix. The author does use a simple retrieval problem to illustrate the efficacy of different retrieval methods and the effect of the constraints employed, and while the example used is illustrative, it might nevertheless have been instructive to have seen a real problem tackled somewhere in the book.

To conclude, I found this book very readable and thoughtfully set out, and found it useful since it brings together the many aspects of inversion mathematics necessary for a more complete understanding of the techniques of remote sensing, although at a price of $65, readers may wish to obtain their copy from a library.

J. S. CAMPBELL

Climates of central and southern Europe, World Survey of Climatology, Volume 6, edited by C. C. Wallén. 300 mm × 210 mm, pp. ix + 248, *illus.* Elsevier Scientific Publishing Company, Amsterdam, 1977. Price: US $67.50.

The climates of four regions of central and southern Europe are described by different authors, but with a common method of presentation.

Chapter 2, on central Europe, including Germany, Austria and Switzerland, begins with an excellent account of the general geographical and climatological features, and then discusses the general circulation in broad terms, but makes clear the characteristics of severe winters such as those of 1928/29, 1941/42 and 1962/63, and, while pointing out that the area receives its main precipitation in summertime, describes how the north-eastward advance of the Azores high may cover central Europe for long spells in the summer, as in 1904, 1911, 1921, 1947, 1959, 1964 and 1971. The annual variation of atmospheric conditions is discussed in terms of the large-scale extended weather types (Grosswetterlagen) as defined by Hess and Brezowsky. A broad seasonal picture is given, followed by monthly characteristics, in which the important synoptic types are described with great clarity, for example the mild westerly types and cold easterly types of winter, and the violent northerly winter storms of the North Sea. The contrasting spring types of southerly föhn and arctic northerlies bringing severe frosts to the northern slopes of the Alps are described with examples and statistics of occurrence. Brief but clear accounts of the early summer monsoon and the predominant thundery col situations of high summer are given. The distinction between the winter and early autumn high-pressure situations is well drawn; the winter type is often meridional, while the autumn type is more zonal with weaker pressure gradients over the area, giving warm sunny days with early morning fog. The great variations in central Europe of continentality and topography, from the northern lowlands to the central highlands and then the Alps, have important influences on the seasonal weather types and these are well described. Maps of the climatic elements are accompanied by a brief text, and the chapter closes with a good list of references and 26 climatic tables. The chapter gives a good brief account of the synoptic climatology of central Europe.

Chapter 3 describes the climate of Poland, Czechoslovakia and Hungary. A classification of circulation types is given, and some examples of weather types, but no clear picture of the synoptic climatology emerges, and even the section on the spatial distribution and annual pattern of the meteorological elements is not very informative.

Chapter 4 on the climate of Italy has a concise account of geographical influences on the climate of the peninsula, emphasizing the barrier effects of the Alpine–Apennine range, and the influence of the Mediterranean, but no synoptic examples are given, even of mistral or bora conditions, although the passage of a winter cold front is illustrated by three-hourly isochrones. The main cyclogenetic areas of the Mediterranean in winter and summer are mapped out, and related to 700 millibar weather types, but without synoptic examples. A brief account is given of variations in the main Italian climatic regions. Mapping of climatic elements is useful, with great detail on thunderstorm and fog frequencies.

Chapter 5 on the climate of south-east Europe consists almost entirely of a description of the main characteristics of the most important climatic elements, emphasizing the effects of the great meridional extent of the area, and those of topography and continentality. It provides little or no information on the synoptic climatology of the region.

The claim on the jacket of the volume that 'all chapters give a review of the atmospheric circulation and its synoptic features' is very inadequately substantiated, and the further claim that 'this book will be of great value in teaching regional European climatology at university level' seems unjustified.

A. F. JENKINSON

Exploring our changing climate, by Tom Williamson. 220 mm × 195 mm, pp. 28, *illus*. London, Her Majesty's Stationery Office, 1977. Price: 75p.

A review of this publication is included in the article by R. P. W. Lewis which appears on pages 147–149 of this issue of the *Meteorological Magazine*.

OFFICIAL PUBLICATIONS

The following publications have recently been issued:

Maps of average annual rainfall over the United Kingdom

Maps of average annual rainfall over the United Kingdom for the international standard period 1941–70 are now available. Rainfall is shown by black isohyets overprinted on an Ordnance Survey 1 : 625 000 map (approx. 10 miles = 1 inch) showing ochre-shaded topography, place names, roads, rivers, and the National Grid.

They are in three parts:

North Britain —England north of a line Seascale (Cumbria) to Ravenscar (North Yorkshire), and Scotland, including the Hebrides, Orkney, and Shetland.
80 × 100 cm. Met. 0.886(NB). £1.00 (plus postage and packing.)

South Britain —England south of a line Seascale (Cumbria) to Ravenscar (North Yorkshire), with an inset showing the Channel Isles.
80 × 100 cm. Met. 0.886(SB). £1.00 (plus postage and packing.)

North of Ireland—Northern Ireland together with adjacent counties of the Republic of Ireland.
30 × 44 cm. Met.0.886(NI). 75p (plus postage and packing.)

Enquiries should be made to Meteorological Office Met O 8c (Room 227), London Road, Bracknell, Berkshire RG12 2SZ, *or* The Superintendent, Meteorological Office, 231 Corstorphine Road, Edinburgh EH12 7BB, *or* The Principal Meteorological Officer (Northern Ireland), Tyrone House, Ormeau Avenue, Belfast BT2 8HH. Weather Centres at Glasgow, Newcastle, Manchester, Nottingham, London, and Southampton have stocks for sale across the counter but they cannot deal with mail order requests. These maps cannot be obtained from Government Bookshops.

NOTES AND NEWS

Changes in senior appointments within the Meteorological Office

The following changes in senior appointments have recently been announced:

Mr F. H. Bushby on promotion to Under Secretary will become the Director of Services of the Meteorological Office on 2 May 1978 following the retirement of Mr G. A. Corby.

Mr D. H. Johnson on promotion to Deputy Chief Scientific Officer will become Deputy Director (Forecasting) on 2 May 1978 in succession to Mr Bushby.

Mr R. J. Ogden will become Assistant Director (Public Services) on 2 May 1978 in succession to Mr Johnson.

Mr C. R. Flood on promotion to Senior Principal Scientific Officer will become Assistant Director (Climatological Services) on 2 May 1978 in succession to Mr Ogden.

Dr R. L. Wiley on promotion to Senior Principal Scientific Officer will become Assistant Director (Systems Development) on 6 June following the retirement of Mr E. J. Sumner.

Aerobiology: a new Assembly of Life Sciences Program

From time to time, the Assembly of Life Sciences* assesses the health of a discipline under its purview through a symposium, study committee, or other device. Aerobiology, a field of study that is engaging the attention of an increasing number of scientists, is the most recent example. From 1967 to 1974, aerobiology was a component of the U.S. International Biological Program (IBP). A major goal of that effort was to develop a basis for international co-operation in mitigating the consequences of atmospheric transport of pathogens, pests, and toxic materials. Among the disciplines involved were meteorology, plant pathology, entomology, allergology, medical mycology, and palynology.

---

* Assembly of Life Sciences, National Research Council, National Academy of Sciences, 2101 Constitution Avenue, NW, Washington, DC 20418, USA.

As a direct consequence, an International Association for Aerobiology was established. This is now recognized as a Commission of the Division of Environmental Biology in the U.S. National Committee for the International Union of Biological Sciences (USNC/IUBS).

In a related move, several scientists associated with the IBP's Aerobiology Program urged the establishment of a Committee on Aerobiology in the Assembly of Life Sciences to see what might be done to further the maturation of aerobiology as a discrete, coherent science and to assist, if judged timely, in launching an American professional society for aerobiology. Other essential tasks of the committee would be to define clearly the limits of aerobiology as a discipline, to characterize its key problems, and to determine how these problems are being met by the various federal agencies. The committee has been appointed and hopes to achieve its primary objectives within three years, after which it will either be phased out or continue as a small subcommittee of the USNC/IUBS to handle international obligations.

Important areas of committee concern include:

Pollen and spore distribution. The results of sampling in a number of sites around the world are tabulated and published annually in the *Statistical Report of the Pollen and Mold Committee of the American Academy of Allergy*. Data on the non-pathogenic species are less readily available. The role of air currents and insects in the transport of pollen throughout the various ecosystems has received scant attention. Rural assemblages of airborne species are very different from those in urban ecosystems and little attention has been paid to airborne plant and animal material in the indoor environment.

Phytopathogens. It is important to ascertain as precisely as possible the exact time that spores or vectors arrive at crop foliage. This would ensure the timely application of pesticides. Air sampling and uniform data formats should enable scientists to forecast the inflow of plant pathogens before disease reaches epidemic proportions.

Microfauna, including insects. Monitoring the movements of insect vectors is important to the health and well-being of humans and animals. Many insects are vectors of plant pathogens. Some species, such as aphids, are carried long distances; others such as leaf-hoppers, mosquitos, house-flies, and moths, are restricted by many factors, including natural barriers and weather conditions. Proper sampling is a very important aspect of dispersion studies. The most effective devices for sampling such delicate organisms as algae and protozoa are bubblers, membrane filters, and exposed culture plates. Little is known of the source of algae in the atmosphere, and no studies have been designed to correlate airborne algae and protozoa with the biota of a given area.

Health of humans and animals. Certain components of the atmosphere directly affect the health of humans and animals, particularly in the areas of allergy and infectious disease. The physical characteristics that endow pollen grains and fungal spores with the capacity for airborne movement are equally responsible for their ability to affect the respiratory tract. Special environmental circumstances can lead to skin eruptions and to hypersensitivity pneumonias in certain occupational groups. Air conditioning and humidification systems have added a new dimension to indoor exposure to airborne allergens.

The peculiar environmental and atmospheric conditions favourable for propagation of specific fungal pathogens (e.g. Coccidioides, Histoplasma) have

long been recognized. The potential for airborne spread of other types of micro-organisms, usually considered contagious only by close contact, is less recognized. There are documented instances when diseases caused by bacteria (anthrax), rickettsia (Q fever), and viruses (foot-and-mouth disease) have spread because of critical meteorological conditions or aerosolization.

Effects of pollutants. Although air pollutants are best known for their direct effect, photochemical oxidants, especially ozone and sulphur dioxide, can inhibit the germination of certain fungus spores and pollens; pollutant gases variously affect the viability of airborne fungus spores and bacteria.

Meteorology. Meteorology is pivotal to aerobiology as it relates to atmospheric transport. Many factors that control the movement of biological materials can be examined by essentially the same physical techniques as can non-living phenomena. Observation (monitoring), quantitative evaluation, and forecasting of these processes are of critical importance to aerobiologists. Certain specialized release mechanisms, the attribute of flight, and the complex aerodynamics of many biological components add extra dimensions to the problem. Intramural transport of bacteria and allergens reflect certain meteorological characteristics of diffusion and turbulence.

Biological particles can also act as nuclei for cloud condensation and for ice formation, can serve as centres of coalescence, and can supply surface-active agents. These roles of the aerobiota are yet poorly understood, but the potential has been clearly demonstrated.

The committee is chaired by Dr Robert L. Edmonds, Director of College Lands, College of Forest Resources, University of Washington. Other members are Drs Donald Aylor, Department of Ecology and Climatology, Connecticut Agricultural Experiment Station; Sheldon G. Cohen, Natural Institute of Allergy and Infectious Diseases; Bruce F. Eldridge, Department of Entomology, Walter Reed Institute of Research; Russell C. Schnell, Mount Kenya Study, U.S. Development Program, Nairobi; Gabor Vali, Department of Atmospheric Resources, University of Wyoming; and Jack R. Wallin, Department of Plant Pathology, University of Missouri.

HARVEY E. SHEPPARD
Staff Officer
Committee on Aerobiology

OBITUARY

We record with regret the death on 8 December 1977 of Mr J. A. Flawn, Senior Scientific Officer, as a result of the tragic aircraft accident at RAF Akrotiri, Cyprus. Jack Flawn joined the RAF Met. Branch in June 1942 and had a variety of war-time postings, at Army establishments at home, and with the Royal Air Force in the Mediterranean and Middle Eastern areas overseas. After demobilization in 1946 he served in all regions of the United Kingdom, mainly at outstations, with a spell of nearly 15 years at Aberporth from 1961 to 1976. He was detached from Aberporth for a time in 1974 to help with the international Atlantic tropical experiment (GATE) and took charge of observations on the *Endurer*, one of the two ships supplied for GATE by the United Kingdom. In 1976 he was posted to Akrotiri. He was a keen and experienced sailor and while in Cyprus he was an active member of the Near East Off-shore Cruising Club.

CORRECTIONS

Meteorological Magazine, April 1977

	As printed	Corrected value
Page 105, Table VI		
1823	93.8	107.0
Pages 106–110, Table VI		
February 1727	204	264
February 1752	144	143
May 1752	222	221
Annual total 1752	2202	2200
Annual total 1760	1900	1902
December 1766	186	185
November 1781	329	239
Annual total 1811	2576	2578
Annual total 1823	2220	2630
Decadal average 1821–30	2688	2719
July 1831	499	490
August 1911	140	146
May 1924	374	324

THE METEOROLOGICAL MAGAZINE

NO. 1270 MAY 1978 VOL. 107

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly Annual subscription £13.14 including postage

Dd. 595890 K15 5/78

ISBN 0 11 724799 5
ISSN 0026–1149